Erupting Dwarf Novae in the Large Magellanic Cloud

Michael M. Shara[1]

American Museum of Natural History, 79th St. and Central Park West, New York, NY,

10024

mshara@amnh.org

Sasha Hinkley

American Museum of Natural History, 79th St. and Central Park West, New York, NY,

10024

shinkley@amnh.org

and

David R. Zurek[1]

American Museum of Natural History, 79th St. and Central Park West, New York, NY,

10024

dzurek@amnh.org

Received ⎯⎯⎯⎯⎯⎯; accepted ⎯⎯⎯⎯⎯⎯

ABSTRACT

We report the first likely detections of erupting Dwarf Novae (DN) in an external galaxy: the Large Magellanic Cloud. Six candidates were isolated from approximately a million stars observed every second night over 11 nights with the CTIO 8K × 8K Mosaic2 CCD imager. Artificial dwarf nova and completeness tests suggest that we are seeing only the brightest of the LMC DN, probably SS Cygni-like CVs, but possibly SU UMa-type cataclysmics undergoing superoutbursts. We derive crude but useful limits on the LMC DN surface density, and on the number of DN in the LMC. Many thousands of cataclysmic variables in the Magellanic Clouds can be discovered and characterized with 8 meter class telescopes.

Subject headings: Stars: Cataclysmic Variables— dwarf novae, galaxies: individual (LMC)

1. Introduction

The study of cataclysmic variables (CVs) in our Galaxy is plagued by the same problem that afflicts so many other areas of astrophysics: uncertainty in the distances to, and hence luminosities of the objects being studied. A second and no less severe problem is the space density and spatial distribution uncertainties caused by our parochial view of the Milky Way. While we can detect erupting Galactic classical novae several kpc from the Sun, most other CVs are located closer than about 500 pc. The reason is simple: novae often achieve 10^5 $L_\odot$, rivaling the most luminous objects in our Galaxy for weeks at a time, while dwarf novae (DN), nova-like variables and their magnetic cousins rarely exceed 10 $L_\odot$. Astronomers have succeeded in cataloguing barely a thousand Galactic CVs in over

a century of searching. Only for a handful are ironclad distances published from Hubble Space Telescope parallaxes (Harrison et al. 1999; McArthur et al. 1999, 2001). Expansion parallaxes for classical novae contribute another 20 or so reasonably secure distances and luminosities (see Warner (1995) for a summary).

It would clearly be of enormous benefit to CV science if hundreds or thousands of cataclysmic variables, all at the same distance, could be located. Accurate luminosity functions, and bias-free period distributions and eruption frequencies would become available to confront inadequately-constrained theoretical models. New sub-classes of CVs might be discovered, and systematic variations in outburst properties and binary orbital distributions would likely be uncovered.

The situation is improving for CVs in a few special places: the crowded cores of globular clusters. Recent detections of dozens of CV candidates in 47 Tuc (Grindlay et al. 2001; Knigge et al. 2002), allow, for the first time, the comparative study of many cataclysmics, *all at the same distance.* Unfortunately, HST and Chandra are essential for followup studies, and these telescopes are two of the rarest commodities in astrophysics. It may be decades before the newly discovered CVs are fully characterized. Worse, many of these CVs probably formed by tidal captures and/or evolved violently under the influences of passing stars. Only one globular DN is easily resolved and studied from the ground: V101 in M5 (Margon, Downes, & Gunn 1981; Shara, Potter, & Moffat 1990). Its rather long (5.79 hour) period (Neill et al. 2002) warns us that it may be anomalous. CVs in the cores of globular clusters have much to teach us, but they're likely to be very different from field CVs.

The outlook is potentially more promising in the Magellanic Clouds. As in the case of globular clusters, all CVs discovered in the Clouds are at nearly the same distance, so direct luminosity comparisons are meaningful. Spatial densities of field LMC and SMC stars are

roughly comparable to those in the neighborhood of the Sun, rather than those typical of globular cluster cores, so tidal encounters almost never happen. CVs in the Clouds must form and evolve via ordinary binary evolution, just as in the field in our own Galaxy. It is certainly true that the metallicities of the red dwarf companions to the white dwarfs in Magellanic CVs will usually be lower than those in the Galaxy. Lower metallicity is a much less drastic effect (Stehle, Kolb & Ritter 1997) than dynamical interactions (Hurley & Shara 2002) in globular clusters, so direct comparisons between Galactic and Magellanic CVs should be extremely fruitful. Finally, the Clouds must be home to 10^6 or more CVs (see below), an enormous sample likely to contain every subtype of CV we know, and perhaps some that we don't yet recognize.

Before carrying out Galaxy-LMC population comparisons, we must, of course find CVs in the Clouds. Since 1897 about 35 erupting classical novae have been spotted in the LMC and SMC. Accurate (1-2 arcsecond) positions for most of these, and recovery of some in deep U, B and V images has recently occurred (Shara, Graham & Zurek 2004). The current sample of quiescent Cloud novae is important to follow-up, but will grow in number only very slowly. This is because all classical novae must recur (Ford 1978) with inter-eruption times of at least 10^4 yr. Thus the many thousands of classical novae that exist in the Clouds will only slowly reveal themselves, via eruptions, over many millennia.

As dwarf novae are a substantial sub-population of CVs which reveal themselves through outbursts every few weeks to months, *almost all* DN in any given field should be identifiable, at least in principle, in a deep survey of order 6-12 months in length. Luminous erupting DN should achieve $U \sim 22.0$, $V \sim 22.5$ near maximum (see section 6) and thus be detectable except in the most crowded LMC fields.

Surveying the entire LMC and SMC often enough to find nearly all erupting DN is a daunting observational program that can and will eventually be undertaken. In this paper

we report a much more modest but realistic feasibility study to demonstrate, for the first time, the existence of erupting DN in the LMC. We also derive a crude estimate of the total number of luminous DN in the LMC.

In section 2 we present the observational strategy and database, while the photometry calibrations are described in section 3. Completeness tests are detailed in section 4, and the six erupting DN candidates are shown in section 5. Simulations of erupting DN in the LMC are compared to these candidates in section 6. We discuss whether the candidates could be other kinds of variables, and the implications for CV numbers and space densities if the candidates are true DN in section 7. We briefly summarize our results in section 8.

2.   Observations

To maximize our chances of detecting erupting LMC DN we requested the longest dark run with the largest telescope (the 4-m)and widest field imager (Mosaic2 8K × 8K) available in 1999 at CTIO. We were awarded the dark nights of 1999 December 2, 4, 6, 8, 10 and 12. All nights were clear, with seeing mostly in the range $1.0 - 1.8$ arcsec. Because DN are usually remarkably blue ($U - V \sim -0.7$ is a good rule-of-thumb; though much redder values do occur (Bailey 1980)) we opted to image our chosen LMC field in U and V filters. Three to eight images were obtained each night in each filter, with total exposure times (typically) of 2.5 hours in U and 1 hour in V. A detailed log is given in Table 1. The plate scale was 0.270 arcsec/pixel, and our total field of view was 1362 arcmin^2 = 0.38 deg^2.

The LMC field we chose is centered at RA (J2000) 05:33:36.7 and DEC (J2000) -70:33:44. The field of view was chosen because five erupting classical novae (the novae of 1948, 1970a, 1970b, 1981 and 1988a) have been observed in the area covered by our CCD array. . . more than any other location in or near the LMC. We were thus able to monitor

these five old novae "for free" while searching for erupting dwarf novae. The results of the old nova monitoring will be reported elsewhere (Shara, Graham & Zurek 2004). An overall view of the location of this field within the LMC is shown in Figure 1, with a magnified view of the eight CCD fields superposed. The field is at the southeastern end of the LMC bar, and crowding is significant. The large surface density of stars hampered efforts to detect faint DN, but was critical to maximize the chances of detecting at least a few bright erupting DN.

The individual Mosaic2 2048×4096 images were combined using the "Montage2" routine contained within the stand-alone DAOphot package. On a given night, individual frames were taken with a total vertical dither of ~ 10 pixels. These frames were run through DAOphot's matching program "DAOmaster" to derive the subpixel frame-to-frame shifts. These shifts were passed to Montage2, which produced a sky subtracted median image of the individual frames.

3. Photometry Calibration

The calibrations were derived from a set of standard magnitudes taken from the central region of M67 as given in Montgomery et al. (1993). To ensure that the central region of M67 was observed on all eight chips, the cluster was observed over two nights on the "right hand" side of the array and then later on the "left hand" side. However, the "left hand" side was observed on the fifth night, and was therefore unusable due to poor seeing. Nevertheless, the zero-points between chips were consistent to within .05 magnitudes, and the zero-points derived for the "right hand" side were used for the entire data set.

Due to the variable seeing, there also exist very subtle differences in the photometry on a night-to-night basis. Thus, in addition to the global zero-point calibration uncertainty

described above, there also exist night-to-night zero-point corrections on the order of .05-.1 mag. These corrections were found by first searching for the least variable (most constant) stars that returned valid photometry for all of the six nights. This was done in an iterative manner to locate stars with variability at least three times less than the average of the ensemble. Once this goal was achieved, a night-to-night average was calculated, and this was subtracted from the photometry of the returned candidates. None of these rather small uncertainties has any effect on the candidate detections and conclusions of this paper.

4. Completeness tests

Accurate photometry and astrometry of any source is limited not only by the source's brightness, but also by the degree of crowding in the field. Simulations were performed to determine the efficiency of recovery of a collection of synthetic stars within a representative sub-region of the dataset as a function of brightness. These simulations use the actual point spread function for a given night and filter, yielding a measure of the effective plate limit and the overall detection sensitivity of these observations and data reductions.

First, the same small sub-region of the entire field was chosen in both the U and V bands and from each of the six nights. The stars in this 500×500 pixel sub-image showed crowding typical of the rest of the dataset (~ 4000 stars in the sub-image). Moreover, the star brightness range in the overall dataset was well matched by the range in this sub-image.

Next, in order to generate a set of synthetic stars, the "addstar" routine contained within DAOphot was used to place 100 copies of the point-spread function randomly across an image and at a set brightness. This was repeated 10 times, for a total of 1000 synthetic stars at a given brightness, night, and filter. Then "allstar" returned photometry on all the stars from these 10 runs. The fraction of the input synthetic stars that were

recovered gives the level of completeness for that given brightness. A synthetic star was considered "recovered" if it was measured within ± 0.5 magnitudes of its input value. The entire procedure was then repeated with a different brightness for the input synthetic stars. A total magnitude range of $\sim 18.5 - 24.0$ for both the U and V filters was covered in increments of 0.25 magnitudes each. The results are shown in Figures 2a and 2b.

Each of the completeness curves reflect well the seeing of each night. For example, the completeness for the third night (best seeing) is 70% at $U = 22$, and 40% at $V = 23$, typical of an LMC DN near eruption maximum. On the fifth night (the worst seeing night) the completeness at these same magnitudes is barely 2-3%. Fortunately every night's imagery except that of night 5 was deep enough and complete enough for us to expect to see at least $\sim 10 - 20\%$ of all erupting DN at or near peak brightness.

5. Candidate Dwarf Novae

For a field with such a high stellar density (~ 1000 stars/arcmin^2), the construction of a good point spread funtion (PSF) is hampered most by neighboring stars crowding the PSF stars. Much effort was expended to automate the search for variables entirely, comparing lists of PSF photometry stars on successive nights. Night-to-night seeing changes produced many candidates in the automated search that were rejected upon visual inspection. Rejection of a candidate invariably occurred because the "candidate" revealed itself to be an artifact created by overlapping PSFs of several stars, changing with the seeing from night to night.

The dwarf-nova candidates were ultimately found by blinking rapidly through the best four of the six nightly frames to look for any subtle changes in the appearance of the stellar field. Dwarf novae should rise from invisibility to easily detectable in the 48 hours

between observations. To look for changes on a fairly detailed level, each chip was visually divided into 32 sub-regions, and blinked rapidly. Brightening from previously empty regions of the sky is easily seen. A star that is ramping up or down in brightness by $0.5 - 1.0$ mags can also be easily detected since the transition between the first and last night is very prominent. Artificial dwarf novae placed in the frames were visually detected with efficiencies similar to the completeness curves of Figure 2.

To be recognized as a candidate, a variable had to be visible in both the U and V medianed frames of at least one of the six nights, and to have varied by over one magnitude in both filters between any two nights. This selection method initially revealed 14 dwarf nova candidates from the entire dataset. A second criterion was then applied to weed out short-period, large amplitude variables: no candidate could vary significantly (more than about 1.0 magnitudes) from frame to frame during any one night. It is certainly true that the light output of many CVs "flickers" on timescales of seconds to hours, and that some CVs undergo short, deep eclipses. We nevertheless adopted this conservative approach to eliminate non-CV, short-period eclipsing binaries. Inspection of each night's individual images confirmed that 7 candidates were likely eclipsing binaries, and one candidate was so crowded that we cannot say for sure that it is a real variable. The eclipsing variables may be useful for LMC distance determinations or other projects, and so we supply their finder charts, and coordinates in Figure 8 and Table 3, respectively.

We are thus left with six good candidate erupting DN. We define a good candidate as one that is seen in both U and V on at least one night; on all images in each filter of that night; and whose variability characteristics are consistent with those of at least one well-studied Galactic dwarf nova (see next section). The nightly images of the six DN candidates are shown in Figure 3, and their photometry is presented in Figure 4. The poisson error is the dominant photometric error in these plots, although readnoise and sky

noise also have been incorporated into the error bars shown. We defer a discussion of these candidates and their implications until after the next section, where we simulate expected DN images and light curves.

6.   Simulations of Known Dwarf Novae

To complement the completeness tests described in section 4, simulations of eruptions of several well known and characterized Galactic dwarf novae, artificially placed in the actual LMC data, were needed. Eruptions of SS Cyg, U Gem, SS Aur, AR And, and EM Cyg were all simulated in a relatively uncrowded but otherwise representative patch of the LMC field (An uncrowded field was chosen to highlight the photometric appearances of LMC DN, unhindered by the crowding or incompleteness addressed in Figure 2). The images from these simulations are shown in Figure 5.

The three dwarf novae SS Cyg, U Gem and SS Aur have accurately determined parallaxes (Harrison et al. 1999) and, using their well tabulated apparent magnitudes (Warner 1995), the absolute magnitudes are easily calculated. The absolute magnitudes for AR And and EM Cygni were obtained from Warner (1995). These five objects were chosen to cover the range of absolute magnitudes seen for erupting and quiescent DN. Our simulated dwarf novae all reflect the rise, plateau, and decline times from Szkody & Mattei (1984), start at quiescence on the first night of observations and attain maximum brightness on the second observing night (48 hours later), have all been placed at the distance of the LMC and, with one exception noted below, use mean $(U - V)$ colors from Bruch & Engel (1994). We have assumed that the LMC DN are dimmed by $A_V = 0.3$ and $A_U = 0.5$, in accord with Clementini et al. (2003). PSF photometry was performed on these frames; the resulting light curves and retrieved photometry are shown in Figure 6.

An additional simulated SS Cygni eruption sequence (labeled "SS Cyg sequence 2" in Figure 6) incorporated more detailed information about this object's color evolution with time. During its eruption, SS Cygni becomes distinctly more red, reaching $(U - V) \sim 0.2$ before attaining maximum brightness Bailey (1980). This second SS Cyg sequence utilizes these colors, and has been shifted by one day in phase. That is, the first simulated observation of this second sequence catches the dwarf nova on the rise. ("SS Cygni sequence 1" shows the artificial DN in quiescence on the first night). This second SS Cyg sequence was included because it mimics rather well the overall observed light curves of DN candidates SHZ1, SHZ4 and SHZ6, though the latter two objects are still redder than the simulated DN. We regard this difference as minor because reddening does vary strongly, and on small spatial scales, across the LMC (Gochermann & Schmidt-Kaler 2002).

It is clear from Figure 5 that we are unlikely to have been able to detect erupting DN like U Gem, SS Aur, AR And or EM Cyg–all are too intrinsically faint to be detected, in our crowded fields. If our candidates are really DN they are much more likely to be SS Cygni, or possibly SU UMa-type CVs in superoutburst.

7. Interpretation

7.1. Have We Found Erupting LMC Dwarf Novae?

Comparison of the six candidates shown in Figure 3 with the LMC-DN simulation images shown in Figure 5 (particularly "SS Cyg Sequence 2" and "SU UMa superoutburst") demonstrates that the brightness and variability behaviors of our candidates are broadly consistent with those expected of luminous erupting dwarf novae in the LMC. This is further supported by comparison of the measured and simulated light curves of Figures 4 and 6, respectively. However, it is by no means certain that all or even some of the six

variables shown in Figure 3 are really LMC erupting dwarf novae.

What are the other possible variables that might mimic LMC DN behavior? Amongst these are: chance superpositions of background supernovae or classical novae, gamma ray bursts (GRB), microlensing events, Milky Way variables along the line of sight to the LMC, and non-CV LMC variables. The microlensing hypothesis can immediately be discarded because of the non-grey light curve behaviors, non-symmetric shapes of the light curves and (in most cases) overly long time at maximum light.

GRB afterglows typically achieve R or I ~ 20 one day after outburst. While the peak brightness of these variables is in accord with the GRB hypothesis, we can eliminate this possibility because none of the candidates declines quickly enough to be a GRB. Large area, multi-epoch surveys for faint variables (e.g. Hawkins & Veron (1987)) show that the surface density of our variables is far too high for them to be field RR Lyraes, classical novae or supernovae.

The brightness and moderately blue colors of the candidates rule out other types of Galactic variables. RR Lyraes in the Galaxy or LMC would be considerably brighter, and flare stars don't match the observed nightly brightness profiles and/or blue colors.

A final possibility to consider is that some of our candidates might be Galactic or LMC eclipsing binaries. Galactic binaries would have to be rather low luminosity systems (say $M \sim 10 - 15$) and thus much redder than observed to appear at $m \sim 20 - 22$. Eclipsing LMC systems would range in luminosity from $M \sim 0$ (SHZ6) to $M \sim 2.5$ (SHZ3 and SHZ5), corresponding to A-type main sequence stars. The amplitudes of light variation in SHZ1, SHZ3, SHZ4, SHZ5 and SHZ6 are greater than 0.7 magnitude and thus preclude equal mass (and brightness) binaries, but a hot pre-white dwarf + a cooler companion star could mimic the observed light curves for SHZ1, SHZ5 and SHZ6.

As noted earlier, we see no sign of significant variability for any of the six candidates on the individual frames taken during the two to five hours of observations during each of the six nights of the run. The candidates' light curves support their tentative identifications as DN, though some may turn out to be other kinds of variables.

To be absolutely certain of these objects' identities will require challenging follow-up observations. Four possible confirmation techniques are the following:

1) Spectra near quiescence (to demonstrate the presence of Balmer emission lines) would be definitive proof, but the DN are then expected to be near 25th magnitude...beyond the likely capability of even an 8 meter telescope in such crowded fields.

2) Imagery every night or two for several months with a 4 meter class telescope should reveal repeated eruptions separated by weeks to months. Such a program would also distinguish erupting CVs from LMC eclipsing binaries, where the emergence of a hot, blue star from eclipse—seen only at one epoch—can be confused with a genuine DN eruption. This can be done, but will be very demanding of large telescope time.

3) Ultraviolet imagery of the fields of the six candidate dwarf novae with the Hubble Space Telescope (HST) might reveal UV-bright objects, as the spectral energy distributions of most CVs rise sharply into the UV.

4) Several hours of time-resolved UV or optical photometry, again with HST, might reveal the flickering and/or orbital modulation characteristic of CVs.

7.2. Expected Dwarf Nova Populations in the LMC

Space density estimates of CVs near the Sun suggest $10^{-5}\,\mathrm{stars\,pc^{-3}}$ (Patterson 1998). Space density estimates of all types of stars in the solar neighborhood yield $10^{-1}\,\mathrm{stars\,pc^{-3}}$,

suggesting that about 1 CV exists in the Galaxy - and probably in the LMC - for every 10^4 stars. The LMC displays a V-band luminosity of -18.1, corresponding to a mass of 10^{10} $M_\odot$ (Cox 1999) and a population of a few times 10^{10} stars.

If the Galaxy and LMC manufacture CVs with similar efficiencies and rates then we estimate a total LMC CV population today of a few times 10^6 objects.

About half of known CVs are DN (Downes et al. 2001) which suggests a total LMC DN population of order 10^6. These DN are spread across the 10×10 degree surface of the LMC. Erupting classical novae are observed to be distributed quite uniformly across the face of the LMC (van den Bergh 1988), consistent with them belonging to an old population. A surface density of 10,000 DN per square degree across the LMC is thus expected.

7.3. Detections versus Expected Detections

The size of our field of view was 1362 arcmin^2 = 0.38 deg^2, which should include 0.38 $\times$ 10,000 = 3,800 DN. The average time between eruptions for 21 well studied Galactic DN is 29 days (Szkody & Mattei 1984). The length of our observing run (11 nights) suggests that any DN erupting on the nine nights between nights 2 and 10, inclusive, could have been detected (if it became sufficiently luminous). Hence $(9/29) \times 3800 \sim 1200$ DN eruptions should have occurred in our field of view that were (at least in principle) detectable.

The 4 meter telescope seeing varied significantly over the six nights on which we observed, as clearly seen in the completeness curves of Figure 2. Only on the second, third and sixth nights were conditions good enough to allow straightforward detection (with 20% to 40% completeness due to crowding) of DN reaching $U \sim 22 - 23$. Assuming (conservatively) that we missed half of all DN because only 3 of 6 observing nights were "good", and that we missed 80% of all eruptions even on the three "good" nights because

of crowding, we might still have expected to have detected $0.2 \times 0.5 \times 1200 = 120$ erupting DN.

The apparent brightness of a dwarf nova depends both on the underlying binary system inclination and orbital period. Nearly face-on disks and longer orbital periods (which have larger and brighter disks) will dominate a magnitude limited sample (Paczynski & Schwarzenberg-Czerny 1980; Warner 1986). High inclination systems will be up to 2 magnitudes fainter than those seen nearly face-on, and will therefore be lost in a sample that is detecting only the brightest tip of the distribution.

Longer period systems will have larger and brighter disks, and thus might be expected to dominate our sample. However, the number of short-period DN ($P < 2$ hr) is twice the number of long-period systems ($P > 3$ hr), and it is these short-period systems that undergo SU UMa-like superoutbursts. SU UMa superoutbursts typically last ~ 3 weeks, and system brightnesses might match those observed for our six candidates. This will be clearer when parallaxes are available for at least a few SU UMa CVs.

The fact that we detected at most six DN when (an admittedly simple) model predicts 120 suggests that many erupting systems were too faint to be detected. This is in accord with the model light curves of Figure 6, and reinforced by the simulated images of Figure 5 showing that DN like U Gem, SS Aur and EM Cyg would all have been missed in our survey, and even (relatively luminous) AR And would have been possible but challenging to detect. What fraction of DN are at least as luminous as SS Cyg or SU Uma at maximum? Unfortunately, the answer is unknown, because the distances to all but four Galactic DN are too uncertain to yield a believable luminosity distribution. (We note that the canonical literature distance to the prototypical DN, SS Cyg, was in error by a factor of two until HST parallaxes became available in 2000). If our six candidates are all bona fide erupting DN in the LMC (of either SS Cygni or SU UMa type) this suggests that 95% of all DN are

less luminous than these prototypical dwarf novae. This percentage rises if fewer than six of our candidates are really DN.

8. Conclusions

We have carried out an 11 day-long survey for erupting dwarf novae in the Large Magellanic Cloud, during which we imaged 0.38 deg^2 in U and V filters on alternate nights. Artificial DN and completeness tests confirm that we imaged faint enough (to 23rd mag on the better nights) to detect SS Cygni-like eruptions. Six candidates were isolated from approximately a million stars observed with the CTIO 8K $\times$ 8K Mosaic2 CCD imager. If these are true LMC DN, then they are amongst the most luminous of outbursting dwarf novae in the Clouds; SS Cygni-like outbursts or possibly SU UMa-like superoutbursts. We estimate the total LMC DN population as 10^6, and the LMC surface density as 10^4 DN/deg^2. This suggests that at least 95% of erupting LMC DN are fainter than the six candidates we present, and were thus missed. An extra magnitude in sensitivity and improvements in spatial resolution will likely lead to the discovery of thousands of DN in the Magellanic Clouds.

While the time coverage we have of the seven variables noted in Section 5 is far too sparse for any attempt at period determination, we include their coordinates in Table 3 and finder charts (in U and V, minimum and maximum) in Figures 7 and 8.

REFERENCES

Bailey, J. 1980, MNRAS, 190, 119

Bruch, A. & Engel, A. 1994, A&AS, 104, 79

Clementini, G., Gratton, R., Bragaglia, A., Carretta, E., DiFabrizio, L., Maio, M. 2003, AJ, 125, 1309

Cox, A.N., editor 1999 Allen's Astrophysical Quantities, 4th edition, Springer-Verlag, New York

Downes, R., Webbink, R., Shara, M., Ritter, H., Kolb, U., & Duerbeck, H. 2001, PASP, 113, 764

Echevarria, J. & Jones, D. 1983, Rev. Mex. Astr. Astrof., 5, 301

Ford, H. C. 1978, ApJ, 219, 595

Gochermann, J., & Schmidt-Kaler, T. 2002, A&A, 391, 187

Grindlay, J.E., Heinke, C., Edmonds, P.D., & Murray, S.S. 2001, Science, 292, 2290

Hawkins, M.R.S. & Veron, P. 1987, A&A, 182, 271

Hurley, J. & Shara, M. 2002, ApJ, 570, 184

Harrison, T.E., McNamara, B.J., Szkody, P., McArthur, B. E., Benedict, G. F., Klemola, A. R., & Gilliland, R.L. 1999, ApJ, 515, L93

Knigge, C., Zurek, D.R., Shara, M.M., & Long, K.S. 2002, ApJ, 579, 752

Margon, B., Downes, R.A., & Gunn, J.E. 1981, ApJ, 247, L89

McArthur, B. E. et al., 1999, ApJ, 520, L59

McArthur, B. E. et al., 2001, ApJ, 560, 907

Montgomery, K. A., Marschall, L. A. & Janes, K. A. 1993, AJ, 106, 181

Naylor, T. et al. 1989, MNRAS, 241, 25P

Neill, J. D., Shara, M. M., Caulet, A., & Buckley, D. A. H. 2002, AJ, 123, 3298

Paczynski, B.& Schwarzenberg-Czerny, A. 1980, Acta Astronomica, 30, 127

Patterson, J. 1998, PASP, 110, 1132

Shara, M.M., Potter, M., & Moffat, A.F.J. 1990, AJ, 99, 1858

Shara, M. M., Graham, J. & Zurek, D. R. 2004, in preparation

Stehle, R., Kolb, U., & Ritter, H. 1997 A&A, 320, 136

Stetson, P.B. 2000, PASP, 112, 925

Szkody, P. & Mattei, J. 1984, PASP, 96, 988

Tody, D. 1986, Proc. SPIE, 627, 733

van den Bergh, S. 1988 PASP, 100, 1486

Warner, B. 1986, MNRAS, 222, 11

Warner, B. 1995, Cambridge Astrophysics Series, Vol. 28 (Cambridge: Cambridge University Press)

Fig. 1.— Field of the LMC imaged in our search for erupting dwarf novae, shown as an insert over the entire LMC. The $8° \times 8°$ image is an R-band MACHO image, while the insert is our $0.61° \times 0.61°$ CCD FOV imaged through a V-band filter. The scale bar on the bottom left is $1°$ long. N is up, E is left in the image. The locations of the six erupting DN candidates are shown as numbered circles in the insert
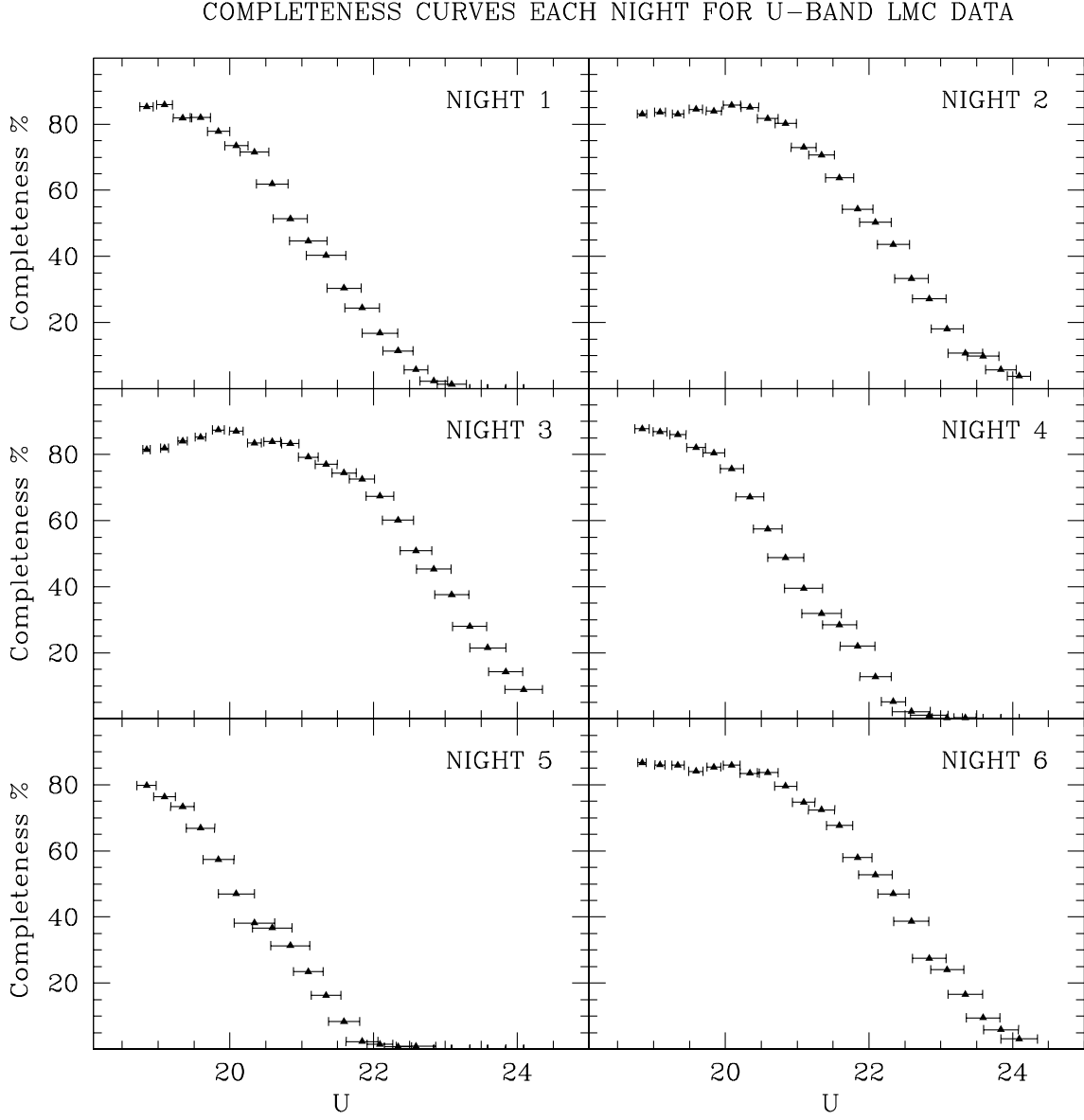
COMPLETENESS CURVES EACH NIGHT FOR U–BAND LMC DATA

Fig. 2a.— Completeness curves for each of six nights of data in the U band images. See text for details.

COMPLETENESS CURVES EACH NIGHT FOR V−BAND LMC DATA
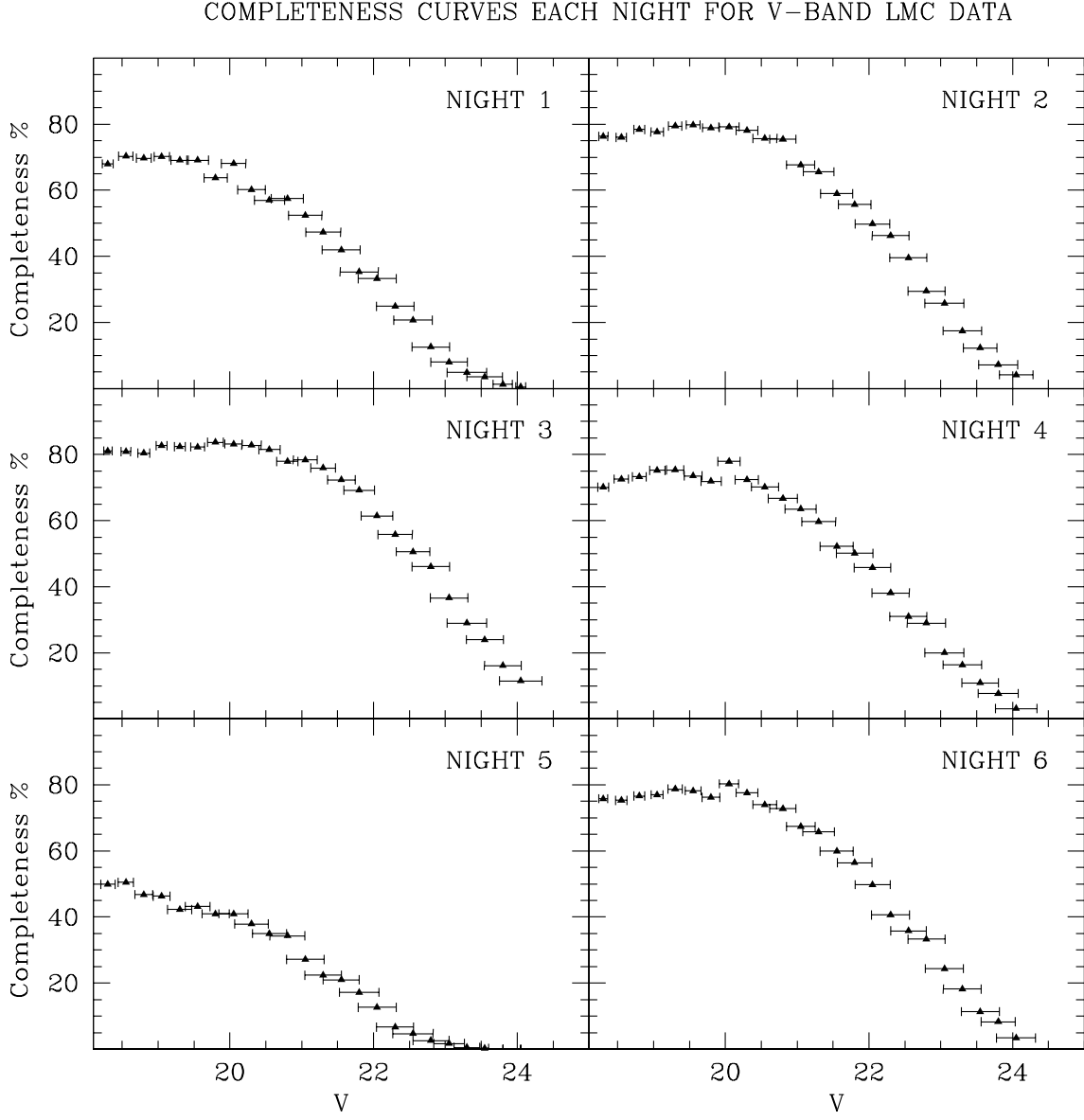
Fig. 2b.— Completeness curves for each of six nights of data in the V band images. See text for details.

SHZ 1

U band

V band

515.16   517.13   519.16   521.11   523.16   525.15   (MJD - 51000)

SHZ 2

U

V

SHZ 3

U

V

SHZ 4

U

V

SHZ 5

U

V

SHZ 6

U

V

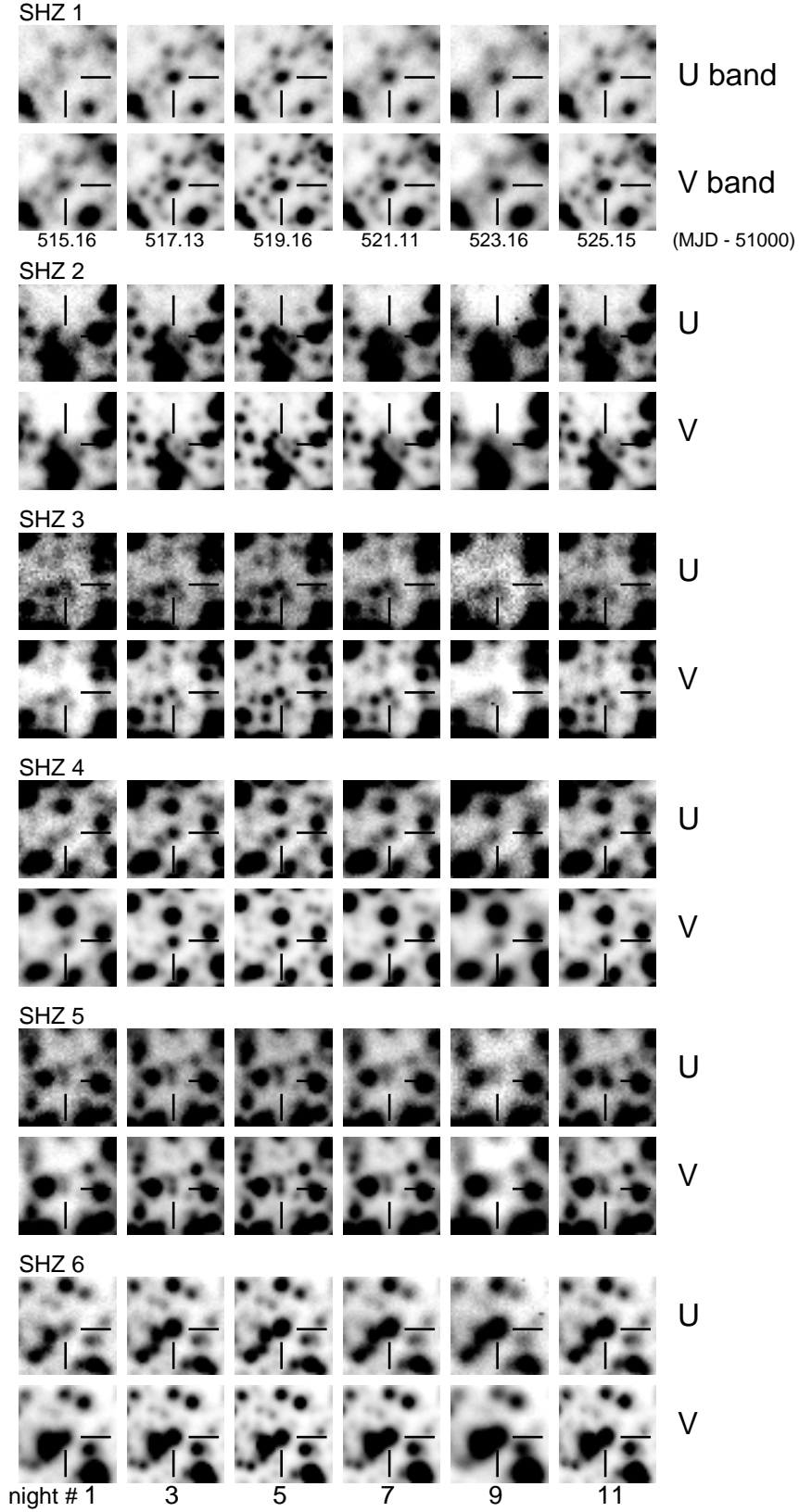night # 1   3   5   7   9   11

Fig. 3.— Nightly medians of images in U and V bands of the six candidate erupting dwarf
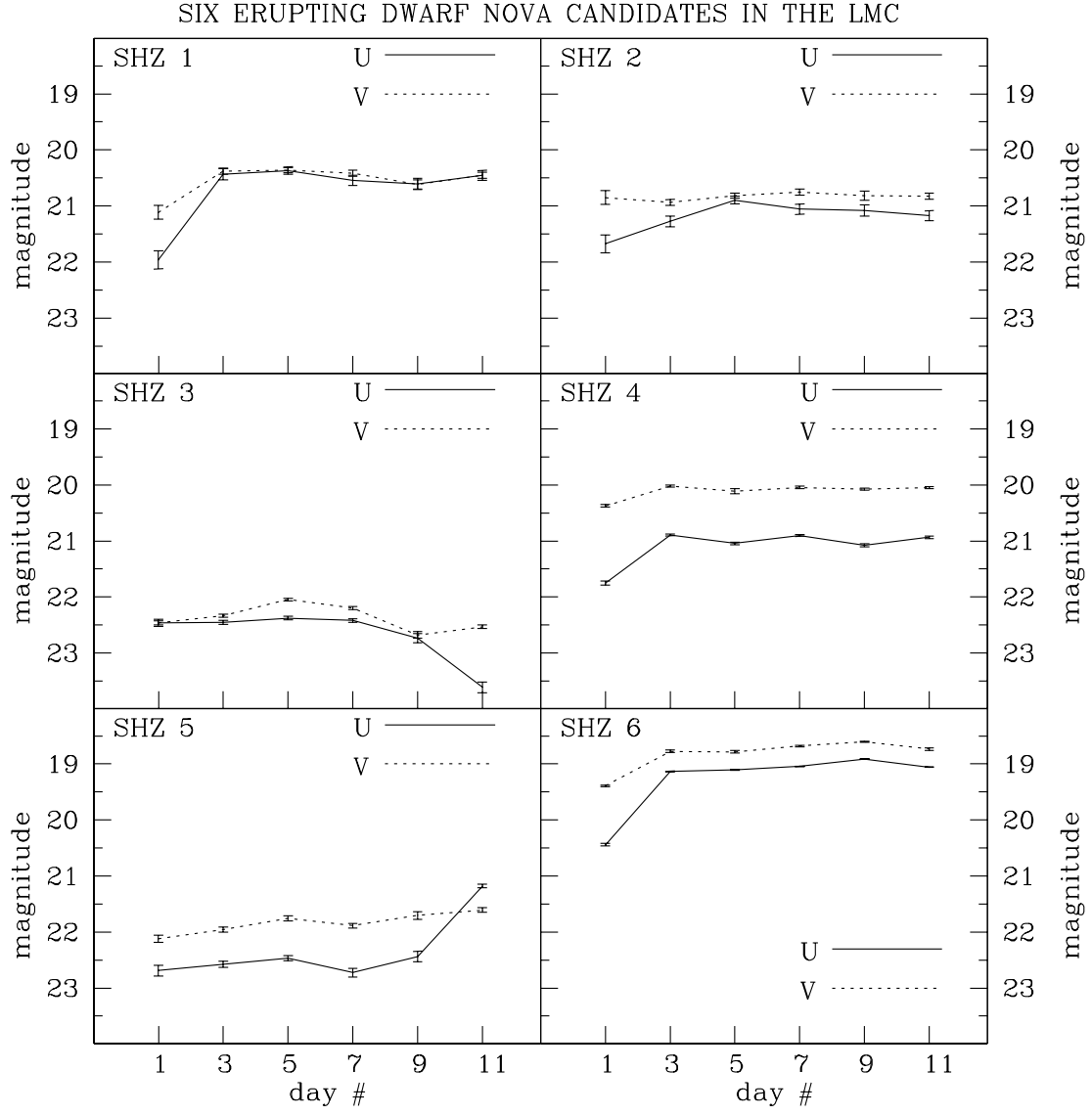
Fig. 4.— *U* and *V* light curves of the six dwarf nova candidates shown in Figure 3.

SS Cyg sequence 1

U band

V band

SS Cyg sequence 2

U

V

U Gem

U

V

SS Aur

U

V

AR And

U

V

EM Cyg

U

V

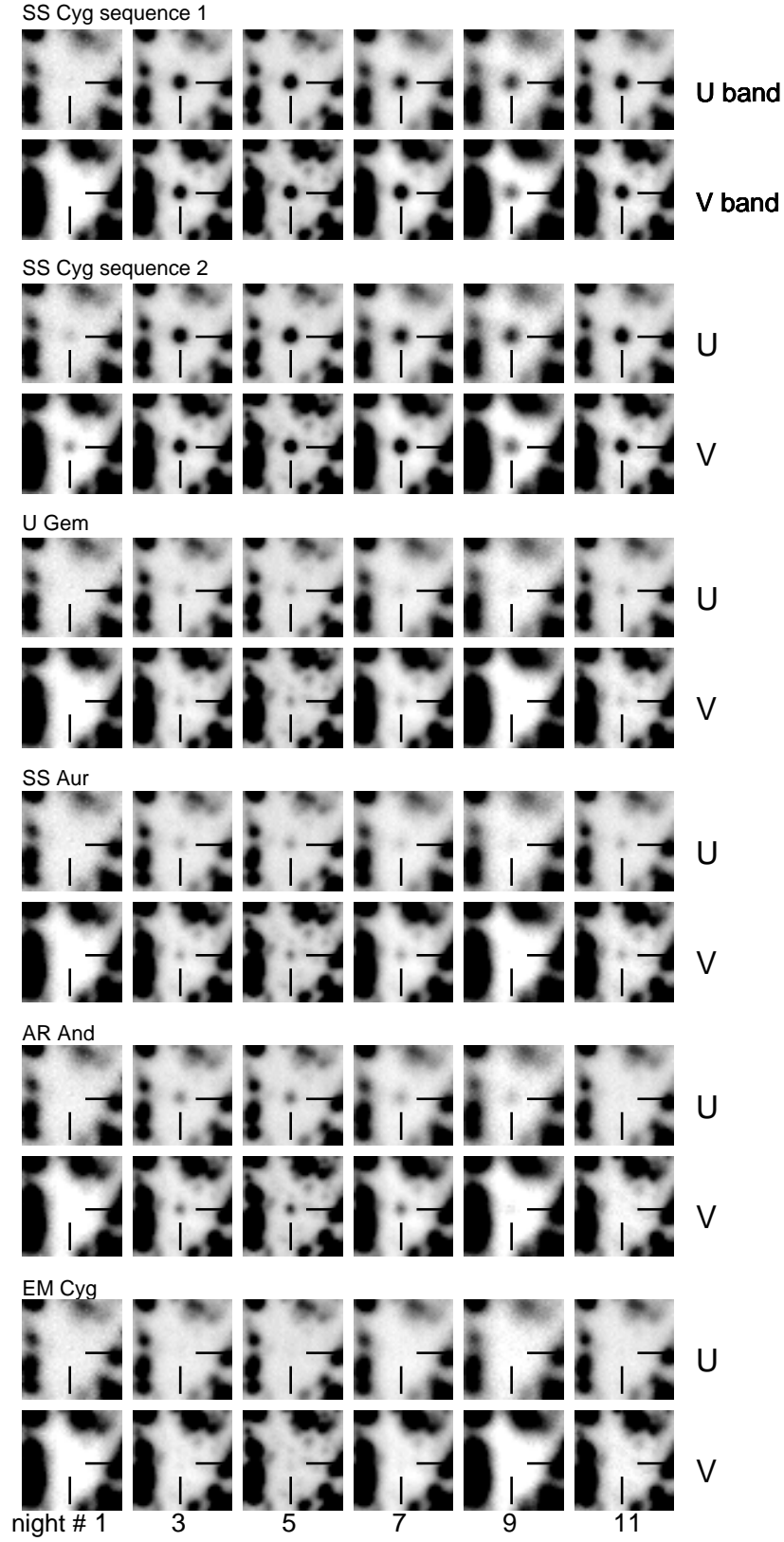night # 1   3   5   7   9   11

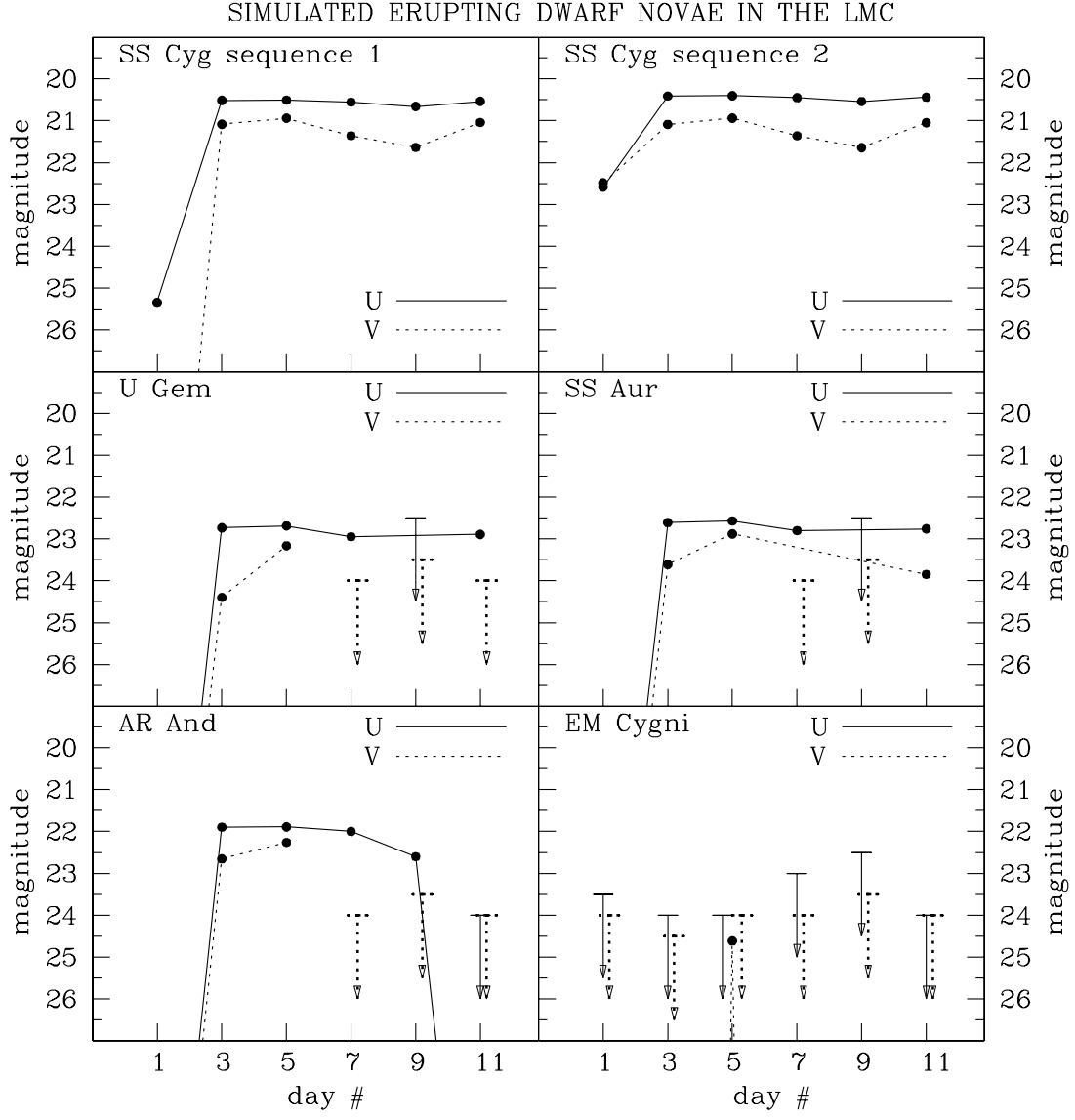Fig. 5.— Simulated images of erupting Galactic dwarf novae placed in the LMC. See text.

Fig. 6.— Simulated light curves of the dwarf novae of Figure 5. The "dips" and magnitude limits on night 9 are due to the particularly poor seeing of that epoch.

U band

V band

max   min   max   min

U band

V band

max   min   max   min

U band

V band

max   min   max   min

U band

V band

max   min   max   min

U band

V band

max   min   max   min

U band

V band

max   min   max   min

U band

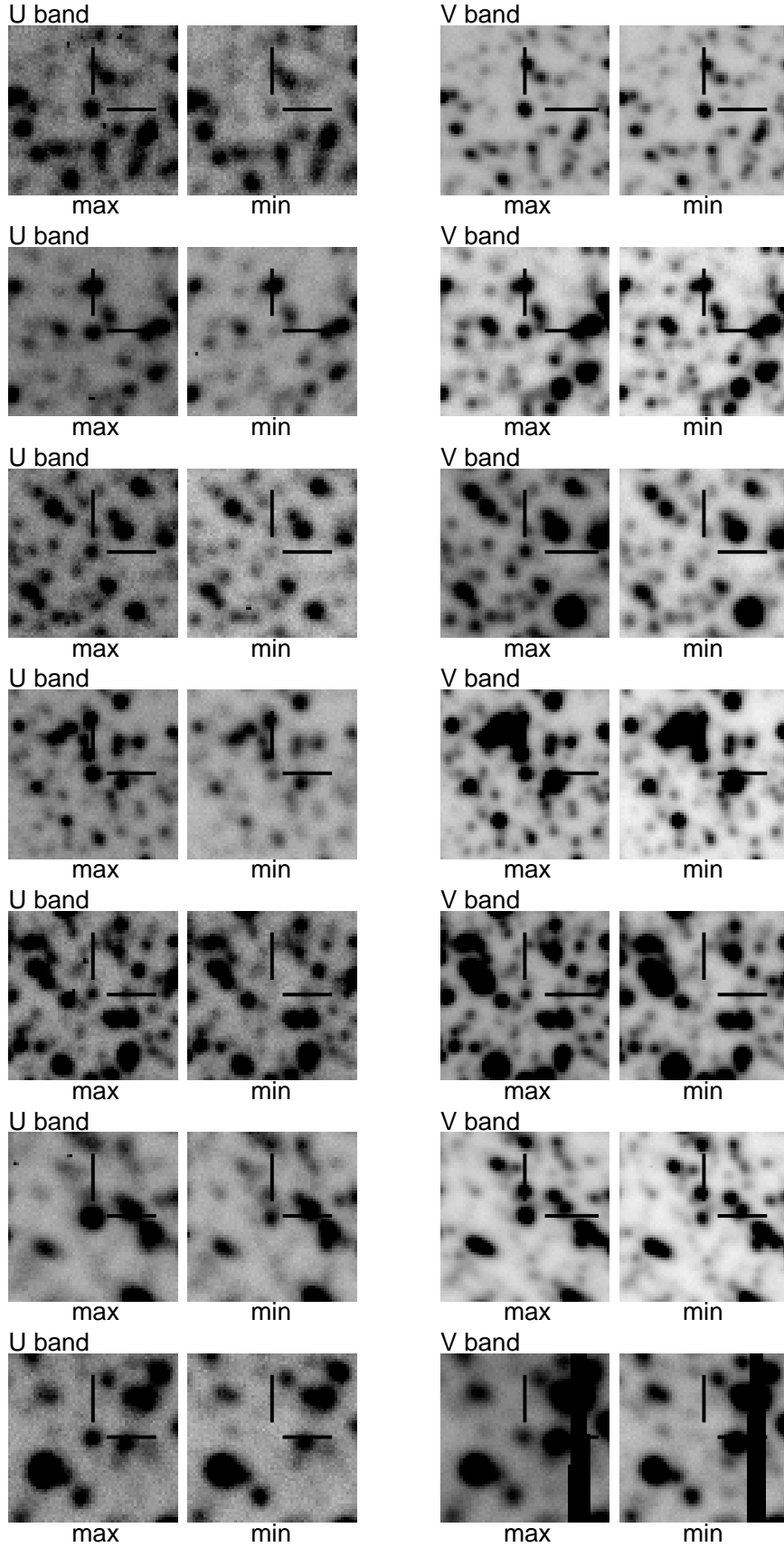V band

max   min   max   min

Fig. 7.— Individual exposures in U and V bands of the seven eclipsing binaries/variables at

Fig. 8.— Same as Figure 1, except the seven variables (probably eclipsing variables) discussed in the text are shown as numbered circles, with prefix "V" in the insert

Table 1.   CTIO 8K x 8K CCD Observations

UT Day	$t_{exp}(U)$ (min)	$t_{exp}(V)$ (min)	U seeing	V seeing	Completeness ($U = 22$)	Completness ($V = 23$)
12.03.99	$3 \times 30 \to 90$	$3 \times 10 \to 30$	1.6"	1.4"	19%	9%
12.05.99	$6 \times 30 \to 180$	$7 \times 10 \to 70$	1.3"	1.2"	52%	27%
12.07.99	$6 \times 30 \to 180$	$6 \times 10 \to 60$	1.3"	1.0"	68%	37%
12.09.99	$7 \times 30 \to 210$	$8 \times 10 \to 80$	1.5"	1.2"	14%	38%
12.11.99	$2 \times 30 \to 60$	$2 \times 10 \to 20$	1.8"	1.7"	2%	3%
12.13.99	$5 \times 30 \to 150$	$3 \times 10 \to 30$	1.3"	1.1"	54%	26%

Table 2.   LMC Dwarf Nova candidate coordinates

Candidate	RA(2000)	DEC(2000)
SHZ1	5:30:42.60	-70:47:32.5
SHZ2	5:31:38.25	-70:38:33.7
SHZ3	5:34:42.07	-70:49:23.6
SHZ4	5:35:10.66	-70:28:02.0
SHZ5	5:35:47.75	-70:24:10.2
SHZ6	5:35:24.47	-70:23:55.4

Table 3.   Variable coordinates

Candidate	RA(2000)	DEC(2000)
V1	5:33:25.77	-70:52:05.7
V2	5:30:45.36	-70:50:42.9
V3	5:33:28.53	-70:46:08.2
V4	5:33:02.97	-70:35:57.6
V5	5:32:33.25	-70:28:48.5
V6	5:31:01.26	-70:18:11.6
V7	5:36:39.89	-70:37:53.5

This figure "Shara.fig1.jpg" is available in "jpg" format from:

http://arXiv.org/ps/astro-ph/0309297v1

This figure "Shara.fig8.jpg" is available in "jpg" format from:

http://arXiv.org/ps/astro-ph/0309297v1